Design and Implementation of an IIoT-based Monitoring System for a Remote Radio Astronomy Station: The CASIRI Case Study

Felipe Rubio, Juan M. Rey, Julian Rodriguez-Ferreira, Natalia Duarte, and Iván Hernández

***Abstract*—Industry 4.0 has progressed rapidly due to advances in the Internet of Things (IoT), which have significantly reduced implementation costs while enhancing technological capabilities. These developments have fostered the emergence of the Industrial Internet of Things (IIoT), particularly within scientific and industrial domains. In response to the growing demand for skilled professionals in this field, this paper presents the design and implementation of an IIoT-based monitoring system for the CASIRI radio astronomy station, a mobile platform used to characterize potential sites for radio observatories in Colombia and Antarctica. The proposed system is integrated into a broader IIoT platform designed to support both operational monitoring and educational activities. The IIoT solution features real-time data acquisition, robust hardware and software components, and reliable communication protocols within a modular and scalable architecture. Its performance and component interoperability were validated through a series of experimental tests under simulated conditions. Additionally, this work introduces educational guides to facilitate hands-on training in Fourth Industrial Revolution technologies.**

Link to graphical and video abstracts, and to code: https://latamt.ieeer9.org/index.php/transactions/article/view/9816

***Index Terms*—Data Monitoring, Education, Industrial Internet of Things, Industry 4.0, Radio Astronomy Station.**

NOTATION

In order of appearance:

IoT	Internet of Things
$IIoT$	Industrial Interent of Things
$CASIRI$	CAracterización de SItios en Radio Interferencias
RFI	Radio Frequency Interference
$LoRa$	Long Range
$M2M$	Machine to Machine
PLC	Programmable Logic Controller
WoT	Web of Things
API	Application Programming Interface
MHM	Machinery Health Monitoring
AWS	Amazon Web Services
SDR	Software Defined radio
$USRP$	Universal Software Radio Peripheral
$FPGA$	Field-Programmable Gate Array
$MQTT$	Message Queuing Telemetry Transport

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I. INTRODUCTION

THE Fourth Industrial Revolution, also known as Industry 4.0, has profoundly reshaped the functioning of various industrial sectors [1]. By integrating advanced digital and physical technologies, Industry 4.0 optimizes processes, improves productivity, and drives innovation. At the heart of this revolution is the Internet of Things (IoT), distinguished by its versatility and adaptability across a wide range of applications including smart homes, healthcare, agriculture, and energy management [2]–[4]. IoT technologies facilitate remote monitoring, control, and management of physical environments, leading to improvements in decision-making efficiency, resource optimization, and process automation [5], [6]. However, as IoT expanded into industrial domains, new challenges emerged concerning stringent reliability requirements, real-time performance, interoperability, and the necessity of operating reliably within harsh or remote environments.

The IoT is defined as a *dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols, where physical and virtual 'things' have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network* [7], [8]. To effectively address industrial requirements, IoT has transitioned into the Industrial Internet of Things (IIoT). Focused on enhancing machine autonomy and interconnectivity within industrial environments, the IIoT integrates sensors, actuators, autonomous devices, advanced industrial communication technologies, and robust software frameworks into advanced network architectures capable of handling large-scale, mission-critical applications [9]. To ensure reliability and security, the IIoT demands robust architectural frameworks that optimize productivity, streamline processes, and reduce costs, substantially impacting how industrial systems are managed [10], [11].

In this context of constant technological evolution, the training of students for designing and implementing IoT and IIoT-based solutions becomes highly relevant [12]. Practical training requires tools that provide strong theoretical foundations and enable hands-on experience. Ideally, these tools should incorporate simulation capabilities within controlled environments, allowing users to explore real-world industrial scenarios to propose solutions to specific challenges [13]–[15].

An interesting area for developing training tools is radio astronomy, a discipline of great industrial and scientific relevance. This field often has applications that require collecting, transmitting, and analyzing large volumes of data. In this context, the IIoT enables real-time monitoring, automating equipment, and optimizing data collection and analysis processes in remote and complex environments.

This paper presents the design, implementation, and validation of a modular IIoT-based monitoring system for a remote radio astronomy station. The case study focuses on the CASIRI[1] station, which is used to characterize potential locations for installing radio observatories. The system integrates meteorological sensors, an all-sky imaging camera, and a radio frequency interference (RFI) detection module.

In addition to its operational function, the station is integrated into an IIoT platform designed to support practical training in Fourth Industrial Revolution technologies, thus serving both operational and educational purposes. Through structured guides and hands-on experimentation, undergraduate and graduate students acquire hands-on experience and practical skills in data acquisition, secure communication, cloud-based platforms, data analytics, and real-time monitoring. This educational component significantly contributes to bridging theoretical knowledge with practical skills, preparing local talent to actively drive scientific and technological innovation within Colombia and the broader Latin American context.

The main contributions of this work include:

- Identifying and describing technical and operational requirements for environmental monitoring and RFI detection at prospective radio astronomy observatory sites.
- Detailing an IIoT architecture, by specifying hardware components, software tools, and communication protocols to ensure reliability, security, and scalability.
- Validating the implemented system through experimental tests to confirm operational correctness, data integrity, and component integration.
- Developing structured educational guides for hands-on activities that leverage the station's capabilities and its integration with an IIoT training platform.

The rest of this paper is organized as follows: Section II provides a review of current IIoT training platforms, emphasizing their role in education. Section III describes in detail the CASIRI station, including operational requirements and system components. Section IV outlines the proposed IIoT system's design, covering hardware, software, and communication protocols. Section V presents experimental validation tests conducted to verify system integration and performance. Section VI presents complementary information regarding data visualization and data hierarchy of the IIoT system. Section VII introduces the learning guides developed for the IIoT training platform. Finally, Section VIII and Section IX conclude the paper, summarizing main contributions and suggesting future research directions.

[1]The acronym CASIRI comes from ***CA**racterización de **SI**tios en **R**adio **I**nterferencias.*, which in English means Characterization of sites in radio interference

II. IoT and IIoT Training Platforms

The rapid evolution of Industry 4.0 technologies demands continuous professional and academic training to maintain effective technical competencies in professionals in the field [16], [17]. In this context, IoT training platforms have emerged as educational tools, enhancing learning experiences through hands-on experimentation, interactive training methodologies, real-time data collection, and remote accessibility [18], [19].

The inherent flexibility and affordability of IoT, enabled by low-cost hardware, minimal infrastructural requirements, and open-source software solutions, allow for the development of economically viable educational platforms suitable for diverse educational settings. Several representative examples of IoT educational platforms demonstrate this potential. For example, Cheng et al. [20] introduced an IoT training system for smart manufacturing education, integrating key domains such as AC/DC distribution system operations, programming languages (e.g., C and Python), and hardware/software co-design. Phan et al. [21] presented educational IoT kits based on LoRa and Raspberry Pi, which are used in university courses. These kits enable the implementation of hands-on projects with specific learning goals, providing students with essential practical experience in IoT technologies.

Similarly, Akbar et al. [22] developed a low-cost modular IoT platform utilizing an industrial controller designed explicitly for control systems training laboratories. This modular platform addresses critical topics, including IoT and Industry 4.0 principles, programming, machine-to-machine (M2M) communication, and web and mobile application development. Also, Pajpach et al. [23] present a low-cost education kit for teaching basic Industry 4.0 skills. The solution is based on Arduino, TensorFlow and Keras, a smartphone camera, and is assembled using a LEGO kit.

Incorporating low-cost microcontrollers further reduces the investment barrier for assembling IoT-based educational setups, enabling remote learning activities without significant infrastructure dependencies. For example, Jacko et al. [24] described the implementation of a microprocessor-based IoT laboratory that allows instructors to monitor students' tasks and programming code remotely. Similarly, Pirrone et al. [25] present a compact hardware and software solution for an open-access remote laboratory. This system uses Python to create a micro-framework with server functionalities while also serving as a control unit for an Arduino microcontroller and a Raspberry Pi microcomputer.

Other educational platforms simulate real-world industrial scenarios, effectively bridging theoretical knowledge and practical industry skills. For instance, Krushnan and Schrödel [26] detailed the creation of a lab-scale Industry 4.0 plant, utilizing advanced technologies to realistically emulate industrial processes. Similarly, within the Tiphys project [27], an open network platform was developed for learning Industry 4.0 concepts, enabling users to design and develop virtual reality-based environments for simulating industrial processes. De

Marchi et al. [28] present an IoT learning factory laboratory where students use IIoT to collect data from machinery and provide a platform for data analytics, monitoring and visualization. Students start with simple, non–Industry 4.0 machinery, and use smart devices to transform it into a cyber-physical system.

To simulate industrial scenarios, various alternatives have been developed under the concept of experimental production lines, small-scale, controlled environments that replicate real-world manufacturing processes. These setups can be implemented using physical modules [29], cyber-physical systems [30], and/or programmable logic controllers (PLCs) [31].

On the other hand, cloud-based platforms allow the application of techniques and tools used in large-scale projects, making them valuable training solutions. For example, Pastor-Vargas et al. [32] present a Web of Things (WoT) platform named LoT@UNED. This platform facilitates remote experimentation within a cloud-based WoT collaborative learning environment, including the analysis of data from IoT sensors. Similarly, Nykyri et al. [33] introduced the IoT Café platform, a simple yet effective educational setup utilizing IBM Cloud and Raspberry Pi edge devices. This platform provides students with valuable practical experience in technologies such as APIs and edge computing, essential components in modern industrial IoT ecosystems.

Modularity is another common element in IoT training platforms. The IoT PEER (IoT Platform for Engineering Education and Research) educational platform is used as a test bed for studying security and smart manufacturing topics. In particular, topics such as Machinery Health Monitoring (MHM) and Intrusion Detection in Industrial/Manufacturing Environments are addressed [34]. Similarly, Loukatos et al. [35] introduce a modular, scalable training solution for IoT-based automation and control in agriculture. To achieve this, retired electromechanical equipment from an old farm was reconditioned using microcontrollers, smartphones, motor drivers, and other low-cost devices.

The diverse IoT training platforms reviewed above illustrate the broad spectrum of available educational solutions, each with distinct strengths and limitations. Collectively, they emphasize the importance of hands-on experience, practical skill acquisition, and real-time monitoring capabilities, bridging theoretical foundations and practical industry relevance. To summarize, Table I provides a comparative analysis highlighting the strengths and limitations of the reviewed IoT educational platforms.

Acknowledging these insights and limitations, the following section introduces and details the IIoT platform designed for training professionals in Fourth Industrial Revolution technologies, which also integrates the mobile radio astronomy station CASIRI.

TABLE I
COMPARATIVE ANALYSIS OF IOT EDUCATIONAL PLATFORMS

Platform Type	Key Strengths	Observed Limitations
Low-cost microcontroller kits	Accessibility, affordability, ease of use kits	Limited scalability, reduced industrial realism
Cloud-based solutions (IBM, AWS)	Scalability, realism, remote access	High costs, high technical complexity
Modular platforms (LabVIEW, Arduino)	Flexibility, modularity	Limited realism for complex industrial scenarios

A. IIoT Training Platform

In Latin American context, IoT training faces unique geographical and socioeconomic challenges. Limited digital infrastructure, budgetary restrictions within educational institutions, and a scarcity of specialized training solutions tailored to local industrial contexts restrict effective technology transfer and professional skill development. Recognizing these limitations and local educational needs, the IIoT platform, currently under development and validation, aims to strengthen competencies in Fourth Industrial Revolution technologies among undergraduate and graduate students[2].

A key feature of this platform is its modular design, initially structured into three distinct application modules, each focused on specific industrial and technological domains. These domains were strategically selected based on an analysis of existing technological challenges and developmental priorities within the Colombian context, resulting in three primary fields of application: agro-industry, energy transition, and technological advancement in radio astronomy.

The agro-industry area is addressed through an application module based on an IoT-enabled automated nursery located on the central campus of Universidad Industrial de Santander in Bucaramanga, Colombia. The energy transition area is addressed through the integration of the monitoring and control stage of an experimental microgrid laboratory [36], located at the Guatiguará Technology Park of the same university. Lastly, the module dedicated to technological development in radio astronomy features the CASIRI radio astronomy station, whose technical details, architecture, and operational components are discussed in the following sections.

B. CASIRI's Distinctive Features

The CASIRI station consists of a series of sensing modules that collectively enable its full range of operational functions. While existing literature includes reports on the application or potential use of IoT technologies in individual systems, such as weather monitoring stations [37]–[40], all-sky cameras [41], [42], and RFI monitoring [43], it is relatively rare to encounter documented implementations within the domain of radio astronomy that combine all these components into a single, cohesive platform. The CASIRI station addresses this gap by presenting a modular IoT-based framework tailored specifically for radio astronomical applications.

Furthermore, one of the most distinctive contributions of this experience is its integration into an IIoT platform designed to

[2] More information can be found on the project website https://www.juanmrey.com/iiot

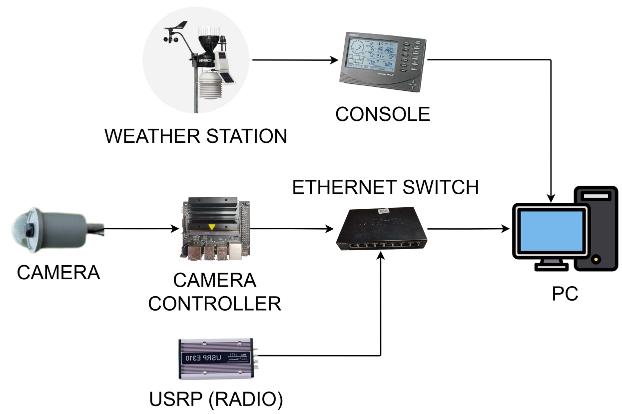

Fig. 1. Scheme of the components of the CASIRI radio astronomy station.

support practical training in Fourth Industrial Revolution technologies. Unlike many platforms described in the literature, which often rely on overly simplified or abstract exercises, this system emphasizes real-world scenarios that reflect the complexities of modern industrial environments. Traditional didactic experiences, such as simply turning on an LED without contextual relevance or operating miniature conveyor belts, frequently result in superficial engagement and limited skill development.

In contrast, the modular IIoT learning platform presented here leverages real-world industrial use cases to provide a more immersive educational experience that facilitates the development of practical competencies aligned with industry expectations. This hands-on, application-oriented approach enhances technical training at the Universidad Industrial de Santander, contributing to the digital transformation of Colombia's industrial sector.

III. CASIRI: A Radio Astronomy Atation

This section provides an overview of the operational features of the CASIRI station, along with the requirements that the IIoT system design must meet to ensure the reliable performance of its monitoring stage.

A. Overview and Purpose

The CASIRI station is a mobile scientific platform designed in 2018 by CEMOS research group at UIS to support the site selection process for future national radio astronomy observatories in Colombia and Antarctica. The station performs in-situ environmental monitoring and RFI detection, both essential for identifying sites with minimal electromagnetic contamination and favorable atmospheric conditions.

The CASIRI station integrates three primary sensing modules: a weather station, an All-sky imaging camera, and an RFI detection unit. The selection of each component was based on technical and operational criteria, particularly focused on robustness, interoperability, and suitability for remote deployment. Fig. 1 presents a schematic diagram of CASIRI.

• **Davis Instruments Vantage Pro 2** was selected for meteorological monitoring due to its accuracy, long-term reliability in harsh outdoor environments, and low energy consumption. It supports real-time measurement of temperature, humidity, pressure, wind speed/direction, and precipitation, key variables for astronomical site characterization.

• The **Oculus All Sky Camera** from Starlight Xpress Inc. was chosen for its specialized design for continuous sky imaging. It features a wide field of view (180°), weatherproof housing, and high sensitivity under low-light conditions, critical for nighttime sky visibility assessments.

• The **Ettus USRP E310** software-defined radio (SDR) was incorporated to detect and analyze RFI. This device was selected for its compact size, onboard FPGA and ARM processor, and compatibility with GNU Radio.

B. Component Interaction and System Integration

The components of the CASIRI station are physically co-located and interconnected through an embedded processing unit (OnLogic ML100G-40 PC), which coordinates data acquisition, preliminary processing, and transmission. The integration follows a modular architecture, where each subsystem operates independently but communicates via standard interfaces.

• The weather station transmits data via serial interface to the local PC, where Python scripts parse and publish the data using MQTT.

• The Oculus camera captures images at scheduled intervals, which are processed locally and stored before upload.

• The USRP E310 autonomously samples RF spectra and forwards processed RFI metrics to the same local server.

All modules are synchronized via the central PC, which acts as the IIoT node responsible for managing MQTT-based communication with a remote cloud server. This decoupled architecture ensures flexibility and scalability, allowing new modules to be integrated with minimal configuration changes.

C. IIoT System Requirements

The key requirements of the IIoT system for the monitoring stage of the CASIRI radio astronomy station focus on ensuring robustness in data acquisition, transmission, storage, and remote visualization.

Data Acquisition (DA)

• *Meteorological Variable Collection:* The system must continuously collect real-time meteorological data from the Vantage Pro 2 station.

• *All-sky Imaging:* The system must integrate the Oculus All Sky camera to capture images of the sky, enabling continuous visual monitoring of the environment.

• *RFI Detection:* The system must ensure continuous monitoring of RFI signals in configurable intervals.

Remote Data Transmission (RDT)

• *Secure and Efficient Data Transmission:* The system must implement a robust communication protocol to ensure the secure and reliable transmission of data from CASIRI station devices to a central server. All measurements must be timestamped and validated before transmission; local backup must be maintained in case of failure.

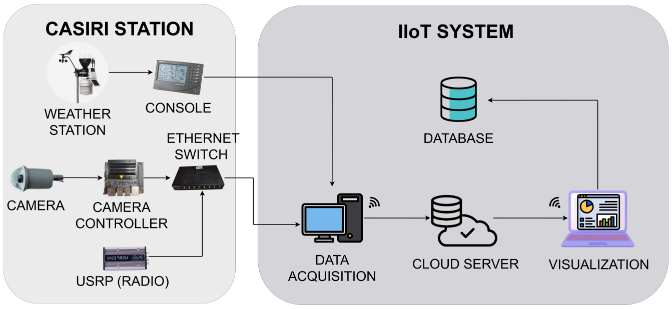

Fig. 2. Proposed IIoT architecture for the CASIRI station.

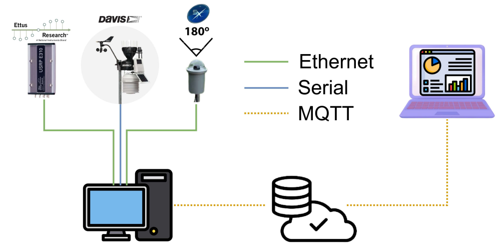

Fig. 3. Communications architecture for the proposed IIoT solution for the CASIRI station.

• *Real-time Remote Connectivity:* The system must enable real-time data transmission, allowing access from any location, including remote and isolated sites.

Data Storage and Management (DT&M)

• *Structured Database:* A scalable database must be implemented to ensure structured storage of collected data. The alternative must allow scalability to easily grow the volume of information.

• *Integration with Monitoring Software:* The system must seamlessly integrate with a monitoring platform that includes a graphical interface, enabling efficient data management and analysis of the collected information.

Remote Visualization and Data Access (RVDA)

• *Real-time Graphical Data Visualization:* Users must be able to visualize live data, download historical records, and remotely configure parameters through a graphical interface.

• *Secure Multi-user Access and Authentication:* The system must ensure that only authorized personnel can access, operate, and manage the systems and data, while maintaining accountability, confidentiality, and integrity.

System Reliability and Scalability (SRS)

• *Robust Operation in Remote Environments:* The IIoT system must be robust and reliable, capable of operating without interruption in remote and adverse environments.

• *Modular and Extensible Architecture for Future Expansions:* The IIoT system should be built with a modular architecture, enabling seamless integration of new devices as needed.

The following section describes the IIoT system design with emphasis on its architecture, as well as the selection of hardware components, software and communication protocols.

IV. Design of the IIoT System

The design of the IIoT system for the CASIRI station follows a modular, scalable, and robust architecture. As shown in Fig. 2 the system is composed of four primary components: the data acquisition interface, a cloud server, a remote visualization solution, and the data storage and management system. Each component was carefully selected to ensure the reliability, performance, and adaptability of the system in remote, harsh environments such as the potential sites for radio observatories in Colombia and other challenging locations.

A. Data Acquisition Interface

This element must meet the *Data acquisition (DA)* requirement, ensuring continuous and synchronized information capture. The sensors of the CASIRI station record climatic variables and sky images, so their integration must reduce data loss during data acquisition. At the heart of the data acquisition subsystem is the OnLogic ML100G-40 PC, chosen for its rugged design and suitability for operation in extreme conditions. In addition, Visual Studio Code was used as the development environment for Python programming, allowing flexible and modular integration with the monitoring devices. Beyond real-time data capture, the selection of this hardware and software contributes to meeting the *System reliability and scalability (SRS)* requirement, providing a robust foundation for future expansion.

B. Cloud Server and Communication Infrastructure

This element must satisfy the requirement of *Remote data transmission (RDT)*, ensuring secure transfer of field-collected information to a cloud server. For this purpose, communication protocols are used to guarantee the integrity and reliability of the data during transmission. Since CASIRI operates in remote locations, the selection of devices and protocols must mitigate connectivity challenges and optimizes bandwidth usage.

For its implementation, MQTT was selected for its lightweight nature, low bandwidth requirements, and ability to efficiently handle intermittent connectivity. This protocol was designed to operate with devices and networks with limited resources and unstable connections [44]. MQTT uses a *publish/subscribe* messaging pattern, where data publishers and subscribers communicate asynchronously via *topics* through a centralized MQTT broker in real time.

In addition, Sparkplug B, a specification that defines the data format and event management in an MQTT-based system, was integrated. In industrial environments, where devices generate large data volumes, Sparkplug B enables hierarchical structuring using nodes (physical devices such as sensors and controllers) and tags (measured variables). The integration of Sparkplug B improves interoperability by standardizing data formatting, simplifying the connection of new devices, and improving failover mechanisms. This directly supports the *system reliability and scalability (SRS)* requirement.

To implement this server in the cloud, HiveMQ Cloud was selected, which provides a scalable and robust platform that guarantees the reliable transmission of data in real time, facilitating interoperability and structured information management. Fig. 3 illustrates the IIoT system architecture, highlighting the communication protocols used by each device.

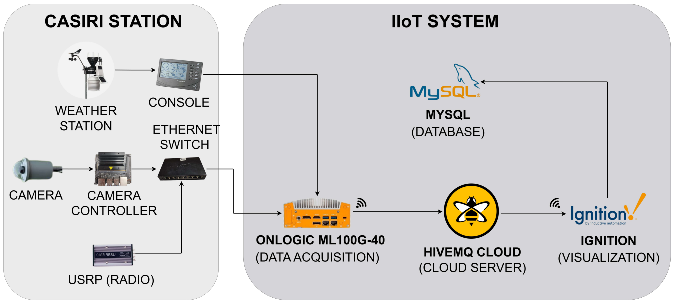

Fig. 4. Proposed IIoT architecture for the CASIRI station with selected components.

TABLE II
CASIRI STATION IIOT SYSTEM DESIGN SUMMARY

Addressed requ.	Component	Functionality
DA	Davis Vantage Pro 2 Oculus All Sky Camera Ettus USRP E310	Collect meteorological, sky imaging, and RFI data
RDT	MQTT Sparkplug B HiveMQ Cloud	Transmit data via MQTT and Sparkplug B
DT&M	MySQL Database Ignition Platform	Store and manage structured data, backup systems
RVDA	Ignition 8.1 Platform web-based UI	Real-time graphical data visualization and access
SRS	OnLogic ML100G-40 PC Python scripts	Manage modular architecture and data flow

C. Visualization Platform

This element must meet the requirement of *Remote visualization and data access (RVDA)*, providing a graphical interface to consult the information in real time. The interface enables users to track meteorological variables, sky images and RFI measurements, ensuring seamless access to information from any location.

For its implementation, a robust environment was required to facilitate system monitoring. Therefore, Ignition 8.1 from Inductive Automation was selected due to its numerous advantages. This software supports unlimited creation of clients, customizable dashboards for visualizing real-time data, role-based access control, and variable management. Additionally, it integrates the MQTT communication protocol and its Sparkplug B extension, enhancing system interoperability. Its web-based architecture allows centralized administration and secures remote access, contributing to the requirement for *data storage and management (DT&M)*.

D. Data Storage and Management

This element is associated with the fulfillment of the requirement *Data storage and management (DT&M)*, ensuring the organization, security, and efficient management of received information. To achieve this, MySQL was selected, an open-source relational database management system widely used in the industry, recognized for its robustness and scalability. Its integration with Ignition enables efficient storage and management of data generated by the IIoT system. Python-based preprocessing scripts ensure that only validated data is transmitted to the cloud and stored for future access. In addition, MySQL offers high performance in queries and transactions, facilitating real-time data analysis and reporting.

The selection of hardware, software, and protocol components associated with each IIoT element meets the design requirements presented in the previous section. Table II summarizes the selected components and their corresponding IIoT requirements. Finally, Fig. 4 presents the IIoT architecture with the chosen elements for implementation, which will be detailed in the next section.

V. VALIDATION TESTS

The methodology used for the validation of the IIoT system implementation in the CASIRI station involved a series of experimental tests designed to verify the correct operation and integration of each of the components to the system. The five proposed tests are detailed below:

A. Test 1: Publishing and Subscribing Data from an MQTT Server.

The first test validates the IoT system's data flow using the MQTT protocol. It was essential to ensure that the data from each sensor could be published to an MQTT broker and that clients (in this case, the cloud server) could subscribe to the relevant topics for data retrieval.

• Objective: Verify that data can be published to the MQTT broker and subscribed to in real-time by the cloud server.

• Procedure: Data generated in Python were published to the MQTT broker. Simultaneously, a client subscribed to the MQTT topics receive real-time data. Visualization is implemented in Python.

• Data sent/received: Text, numbers or any other data in plain format.

• Expected Outcome: Real-time transmission of data generated in Python without significant delay or packet loss.

This test confirmed that the MQTT protocol was working as expected, ensuring stable and reliable communication between clients-publishers, the broker and clients-subscribers. Fig. 5 presents the schematic of the Test 1 implementation.

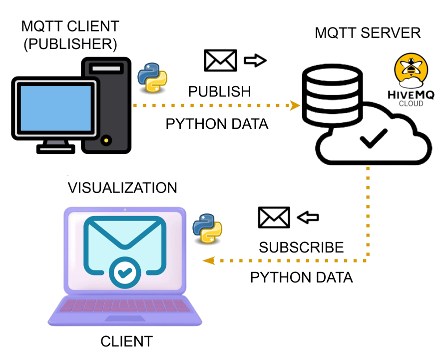

Fig. 5. Scheme for Test 1: Publishing and subscribing data from an MQTT server.

B. Test 2: Visualization in Ignition using MQTT with Data Generated in Python

The second test focused on the integration of the MQTT communication protocol with the Ignition 8.1 platform.

• Objective: Ensure that MQTT data can be received by Ignition and visualized accurately on custom dashboards.

• Procedure: A Python script was used to simulate sensor data, which was published via MQTT. Ignition, configured as the data visualization platform, subscribed to the MQTT topics and displayed the incoming data on custom dashboards.

• Data sent/received: A randomly generated numeric value using Python.

• Expected Outcome: Data was successfully visualized in real-time on the Ignition platform without issues such as data loss, incorrect formatting, or delayed updates.

The test results indicated that the system is capable of real-time data visualization, effectively bridging the communication layer with user interfaces. Fig. 6 illustrates the schematic implementation of Test 2.

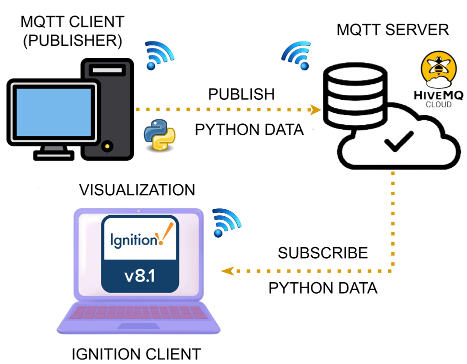

Fig. 6. Scheme for Test 2: Visualization in Ignition using MQTT with data generated in Python.

C. Test 3: Integration of the Davis Vantage Pro 2 Weather Station with Ignition via MQTT

This test aimed to evaluate the functionality of the Davis Vantage Pro 2 weather station and its integration with the Ignition platform through MQTT.

• Objective: Verify that the weather station can successfully transmit data to the central server, which would then be visualized on Ignition dashboards.

• Procedure: The weather station was connected to the ML100G-40 PC, where Python scripts parsed and published the meteorological data to the MQTT broker. Ignition then subscribed to the data and visualized it in real-time.

• Data sent/received: Data obtained from a Davis Vantage Pro 2 weather station. The data include temperature, humidity, atmospheric pressure, wind speed and direction.

• Expected Outcome: Accurate weather data visualization on the Ignition platform, with the system handling data in real-time without significant delays.

The test confirmed that the weather station integrated seamlessly with the visualization platform, providing real-time data as expected. Fig. 7 illustrates the schematic of the Test 3 implementation.

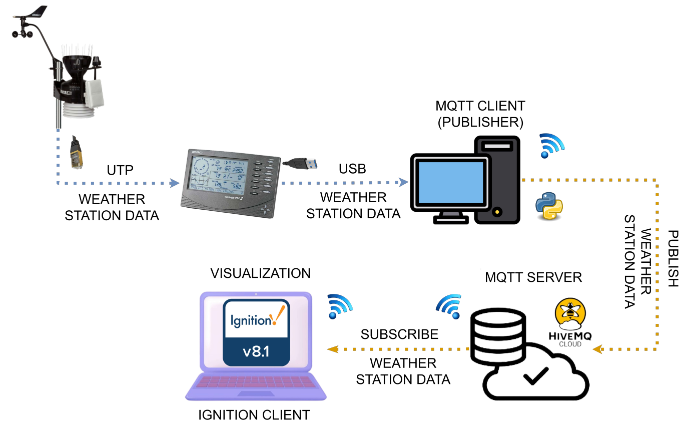

Fig. 7. Scheme for Test 3: Integration of the Davis Vantage Pro 2 Weather Station with Ignition via MQTT

D. Test 4: Sending Data using Sparkplug B and Displaying in Ignition

This test focused on ensure that data transmitted using Sparkplug B could be correctly visualized in Ignition.

• Objective: Confirm that Sparkplug B enables the system to structure, transmit, and visualize data efficiently.

• Procedure: Sensor data was transmitted using the Sparkplug B specification, which includes hierarchical topic structures and payload formats. Ignition subscribed to the topics and displayed the data in an organized manner.

• Data sent/received: Data obtained from a Davis Vantage Pro 2 weather station. The data include temperature, humidity, atmospheric pressure, wind speed and direction.

• Expected Outcome: Real-time visualization of data in Ignition, with clear hierarchical structures and accurate data representation.

The test successfully demonstrated that Sparkplug B integration worked as intended, allowing for organized and real-time data visualization in Ignition. Fig. 8 illustrates the MQTT protocol connecting to an Ignition client with Sparkplug B implementation.

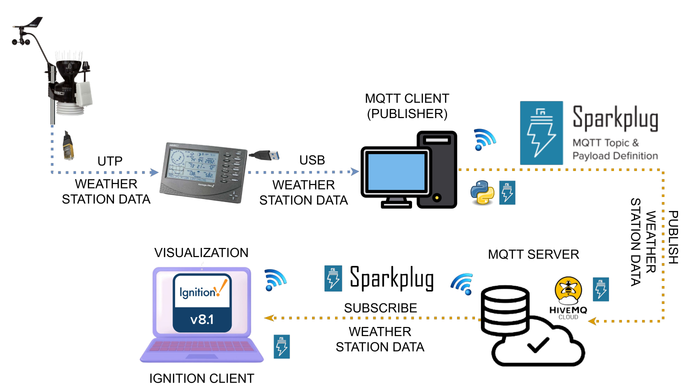

Fig. 8. Scheme for Test 4: Sending data using Sparkplug B and displaying in Ignition.

E. Test 5: Backup, Data Storage, and Visualization in Ignition

The final test focused on the database and backup systems, which are essential for ensuring that data is securely stored and can be accessed for historical analysis. This test also assessed the integration between the storage system and Ignition.

- Objective: Ensure that data is correctly stored in the database and that historical data can be visualized in Ignition.
- Procedure: Sensor data was published to the MQTT broker, stored in a MySQL database via Ignition, and visualized on dashboards. The backup system was tested by simulating a temporary loss of connectivity, during which data was stored locally and later synced once connectivity was restored.
- Data sent/received: Data obtained from a Davis Vantage Pro 2 weather station. The data include temperature, humidity, atmospheric pressure, wind speed and direction.
- Expected Outcome: Data retention and recovery worked seamlessly, and historical data was visualized without issues when access to the database was re-established.

The results showed that the backup and storage systems were functioning as expected, with data correctly stored, archived, and retrievable for later visualization. Fig. 9 presents the schematic of the implementation of test 5.

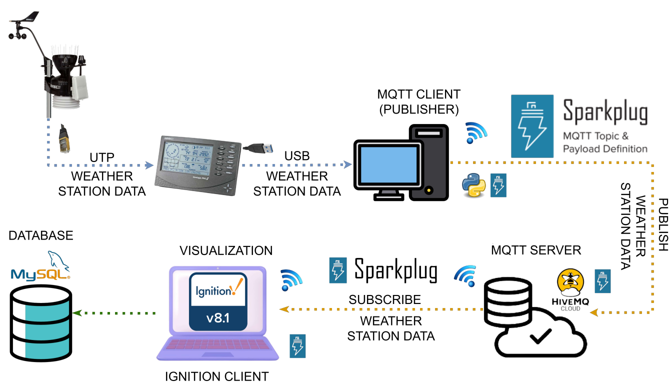

Fig. 9. Scheme for Test 5: Backup, Data Storage, and Visualization in Ignition.

The series of validation tests confirmed that the IIoT system implemented for the CASIRI station meets all functional and operational requirements. In April 2025, a field validation of the complete CASIRI system under real operational conditions at the Páramo de Santurbán, Colombia, was conducted. This validation allowed to assess the functionality of each individual subsystem, from data acquisition and transmission to visualization and storage, as well as the overall operation of the fully integrated radio astronomy station. Fig. 10 shows a photo of the first field test.

VI. IIoT System Deployment

A. Data Visualization

To support the visualization of monitored variables, a user interface was developed using Ignition. This interface provides essential tools for real-time data display and historical data queries. Fig. 11 shows a screen displaying an image by the All-Sky Camera, alongside the corresponding measurement location on a map. The screenshot was taken during configuration tests conducted at the Universidad Industrial de Santander in Bucaramanga, Colombia. A link to a repository is provided

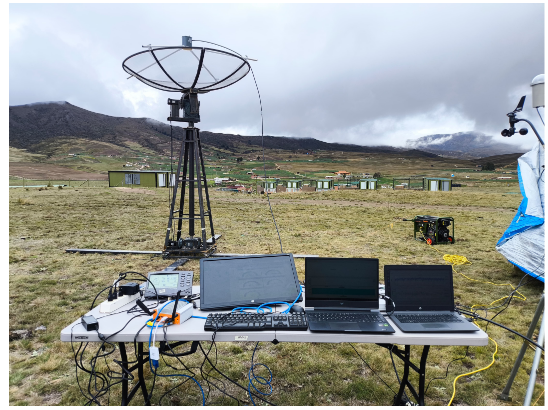

Fig. 10. Photo of the CASIRI radio astronomy station in the first field test.

in the final section of this paper, which includes step-by-step documentation of the experimental tests and additional interface screenshots.

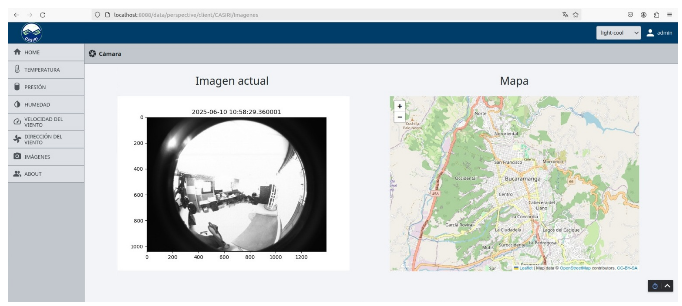

Fig. 11. Example of the user interface - Capture display screen of the All Sky Camera.

B. Data Hierarchy

The data structure adheres to the Sparkplug B hierarchical model, which organizes information by Edge Nodes and Devices. Each node publishes metrics under well-defined topics following the namespace format:

spBv1.0/group_id/edge_node_id/device_id

This structure ensures consistent, traceable, and scalable data exchange between system components.

This hierarchy is applied in Test 4, as illustrated in Fig. 12. Data from the weather station is first processed by an edge device acting as an MQTT publisher. The device formats the data in compliance with the Sparkplug B specification and transmits it to HiveMQ, which operates as the central MQTT broker. HiveMQ receives and parses the messages, making the data accessible for both real-time visualization and historical logging through an Ignition client.

The modular system architecture enables seamless interoperability across hardware, communication protocols, and software platforms.

VII. Pedagogical Strategy

The integration of the CASIRI station into an IIoT educational platform is a key component of the broader strategy

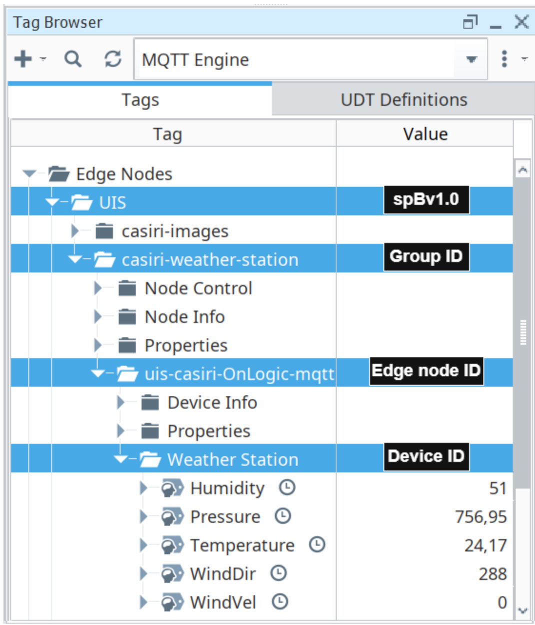

Fig. 12. Sparkplug B hierarchy applied to the IIoT architecture for the CASIRI station.

to develop professional competencies in the technologies of the Fourth Industrial Revolution at Universidad Industrial de Santander. The platform aims to provide hands-on learning experiences that bridge the gap between theoretical knowledge and real-world industrial applications. This section outlines the learning guides developed for the platform and the learning outcomes that are expected to be achieved by students engaged in the training process.

A. Structure of the Learning Guides

To facilitate the learning process, a series of structured learning guides have been developed. These guides are designed to lead students through the various stages of working with IIoT systems, from basic data collection and processing to advanced system integration and remote monitoring.

The guides are divided into four main modules. Each module is divided into specific activities that guide the learner step-by-step through the concepts and tasks, ensuring that each student gains practical experience at every stage.

- **Module 1 - Introduction to IIoT Systems:** This module introduces the basic concepts of IIoT, including data acquisition, communication protocols, and the architecture of a typical IIoT system.
- **Module 2 - Data Acquisition and Transmission:** This module focuses on the operation and integration of sensors, including the weather station, all-sky camera, and RFI detection unit. Students will learn how to configure sensors, collect data, and transmit it using MQTT.
- **Module 3 - Real-Time Data Visualization and Analysis:** Students will explore how to visualize and analyze the data collected from the CASIRI station using platforms like Ignition 8.1. This module emphasizes the use of dashboards, real-time monitoring, and historical data analysis.
- **Module 4 - System Integration and Scalability:** This module delves into the integration of the entire IIoT system, including data storage, cloud-based communication, and system scalability. Students will learn how to extend the system with additional sensors or modules.

B. Teaching Methodology

The pedagogical approach follows a project-based learning methodology, where students engage in structured projects that simulate real-world scenarios. The approach includes:

- Hands-on experiments: Students interact directly with the CASIRI system, operating sensors, analyzing data, and configuring software tools to gain practical experience.
- Guided activities: Each module contains a series of tasks that lead students through the learning process, with built-in explanations and troubleshooting tips to assist them in overcoming potential challenges.
- Collaborative learning: Students are encouraged to collaborate with peers, share ideas, and solve problems collectively, mimicking real-world industrial teamwork environments.
- Continuous assessment: Assessment is integrated into the learning process through practical assignments, quizzes, and project reports that evaluate the students' ability to apply theoretical knowledge to practical scenarios.

This methodology ensures that students not only gain technical knowledge but also develop the problem-solving and teamwork skills that are essential for the modern industry.

C. Learning Outcomes

By completing the learning guides, students will achieve:

- Comprehensive understanding of IIoT systems: Students will understand the key components and technologies that make up an IIoT system, including data acquisition, communication protocols, cloud computing, and visualization tools.
- Practical experience in IIoT implementation: Students will gain hands-on experience in configuring and operating real IIoT systems, including sensors, communication protocols, and data visualization platforms.
- Ability to troubleshoot and optimize IIoT systems: Students will be able to identify and solve technical problems related to IIoT systems, optimizing system performance and ensuring data integrity.
- Teamwork and collaboration skills: Through collaborative projects, students will develop communication and teamwork skills, preparing them for careers in industrial settings where collaboration is key.

VIII. Conclusions

This paper presented the design, implementation, and validation of the CASIRI IIoT-based monitoring system. The integration of IIoT technologies, including real-time data modeling, secure transmission, and cloud-based visualization, demonstrated the potential of CASIRI to support both scientific research and educational objectives. The experimental validation tests confirmed that the system meets all key operational requirements, including real-time data collection, reliable transmission, seamless integration, and robust performance under simulated field conditions. The performance of the full system was validated on a first field test, conducted in April 2025. Furthermore, the pedagogical strategy incorporated into the system ensures that students are provided with a hands-on learning experience, bridging the gap between theoretical knowledge and practical application in IIoT technologies.

This project also highlights the importance of local adaptation, with CASIRI specifically designed to operate in particular conditions, where limited infrastructure and challenging weather demand robust and autonomous systems. This adaptability allows CASIRI to be used in other regions with similar environmental and logistical constraints.

IX. Future Work

In addition to the validation campaigns conducted in Colombia, a simplified version of the CASIRI system has been successfully deployed and tested in Antarctica during three scientific expeditions of the Colombian Antarctic Program: EAC IX (2023), EAC X (2024), and EAC XI (2025). Field trials were conducted both at the General Bernardo O'Higgins Base (63'19'15"S, 57°53'59"W), located on Isabel Riquelme Islet in the Covadonga Bay of the Antarctic Peninsula, and at the Joint Scientific Polar Station Glaciar Unión (79°45'S, 82°30'W) in Ellsworth Land, within the deep Antarctic interior. During these campaigns, CASIRI operated under extreme environmental conditions, including temperatures down to -40°C and sustained high winds. The system was tested in both short-duration and continuous 48-hour sessions powered by batteries, confirming its robustness in polar conditions.

Future developments of the CASIRI platform will focus on evolving the system into a fully autonomous, Antarctic-ready configuration. Drawing upon the design and operational lessons learned, we aim to adapt CASIRI to withstand permanent exposure to harsh polar environments. This includes improving thermal insulation, optimizing power management for prolonged battery-based operation, and ensuring reliability of communication and storage systems during long Antarctic winters. Additional multi-season campaigns will be planned to validate the upgraded system under real-world constraints, enabling its broader application in polar science, space analog missions, and remote monitoring in extreme environments.

Repository

A GitHub repository is available at the following link: https://github.com/uis-dautom/CASIRI. The repository contents:

- Scripts: Python code for data simulation, MQTT publishing, and system validation.
- Validation videos: Step-by-step documentation of experimental tests.
- Learning guides: Structured educational materials covering basic IoT concepts to advanced IIoT implementations.
- Ignition backup: Complete project with functional dashboards for remote visualization of atmospheric variables.
- Technical documentation: Descriptions of system architecture, components, tests, and scalability considerations.

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